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FIFTH QUARTERLY PROGRESS REPORT

1 October 1962 - 31 March 1963

HIGH POWER SEMICONDUCTOR

PHASE SHIFTING DEVICES

Contract NObsr - 87291

Project Serial No. SR 008-03-02

Task 9637

Navy Department Bureau of Ships

Electronics Division

MICROWAVE
ASSOCIATES,
INC.



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This contract constitutes a direct extension of the work done on Contract NObsr - 81470, entitled "Phase Shifter Study (Non-Ferrite)," which terminated with the Sixth Quarterly Progress Report.

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June, 1963

MICROWAVE ASSOCIATES, INC.

BURLINGTON, MASSACHUSETTS

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ABSTRACT

- 1) During the last quarter a high average power L band step phase shifter was tested.
- 2) Measurements of a step phase shifter using a strip line hybrid coupler were made to determine the peak power capability as a function of the number of degrees of phase shift obtained.
- 3) An iterative loaded transmission line type of phase shifter is proposed in coax line at S band.

PART I

PURPOSE

The purpose of this work is to investigate microwave phase-shifting techniques, excluding ferromagnetic and mechanical methods, to make recommendations for new phase-shifting techniques which provide improved electrical scanning, and to develop models of a phase shifter utilizing these techniques.

GENERAL FACTUAL DATA

The purpose of this program is to recommend semiconductor phase shifting techniques which show promise and to furnish engineering models employing the techniques involved.

The study program for the past quarter had these aspects.

- 1) Test of a step phase shifter employing the water cooled diodes discussed in the previous report, and
- 2) Measurement of the peak power performance of a step phase shifter as a function of the number of degrees of phase shift obtained, and
- 3) Design of an iterative loaded transmission line type phase shifter at S band.

IDENTIFICATION OF PERSONNEL

K. Mortenson	Physicist
L. Mesler	Semiconductor Engineer
J. White	Microwave Circuit Engineer
R. Galvin	Characterization Engineer
H. Griffin	Associate Circuit Engineer

Biographies of the above personnel have been included in the first and second quarterly progress reports.

DETAILED FACTUAL DATA

A. General Comments

In previous reports under contract NObsr-81470, it has been shown that semiconductor devices such as currently being investigated at Microwave Associates, can yield the desired phase shifting components required for the microwave region. Further, single continuous phase shifting devices have been built to yield over 130° of phase shift per decibel of insertion loss at L-band; and as much as 270° of phase shift was obtained using a single hybrid coupler with varactor diode terminations. The problems associated with semiconductor phase shifting devices, such as peak power handling capabilities, average power dissipation, and for the varactor phase shifter, power sensitivity of the phase shift, have been discussed previously. Basically, the peak power capability of the semiconductor device is determined by its voltage breakdown; the power dissipation or average power capability by the thermal dissipation and the Q of the diodes, since most of the power seen by the device is reflected. The power sensitivity of a varactor phase shifter may be reduced by using only a small portion of the reverse voltage swing of the diode for phase shifting. However, this puts an extreme requirement on the reverse breakdown voltage of the varactor which is used to handle large RF power, even when this effect is minimized by use of the back-to-back mounting described in the second quarterly report.

B. Step Phase Shifting Techniques

Previous reports (contracts NObsr-81470 and NObsr 87291) have discussed

the theory and techniques of step phase shifters utilizing PIN diodes in either the open or short circuit condition in front of a short circuited line. Iterative loading of a transmission line by lightly coupled switched shunt susceptance values can be used to provide discrete increment phase control. Progress made in these areas will now be discussed.

1. The High Average Power Phase Shifter

During the last quarter high power testing was performed on a phase shifter using two water cooled diodes in shunt with each of the 3 db arms of a hybrid coupler. Located a distance down the transmission line behind the diode plane was a short circuit. The position was adjusted symmetrically in each arm so that a phase shift of 90° was obtained by switching the diode bias from +100 ma per diode forward bias to -100 volts reverse bias. The insertion loss at 1300 mc was equal to 0.35 db under forward bias and 0.29 db under reverse bias. Input VSWR was 1.1.

A high power continuous wave RF source was not available so testing was performed at a pulse length of 500 microseconds and 750 watts peak, and this was successfully sustained for the forward conduction state of the diodes. Such long pulse length operation is believed to simulate closely high power operation because its duration is commensurate with the thermal time constant of the diodes--of the order of 1 millisecond.

The peak RF power limitation of the phase shifter was determined by the maximum allowable voltage appearing across the diode in the reverse biased state. Since the diode breakdown voltage was 1000 volts and a reverse bias of -150 volts would be used typically to prevent diode conduction with an applied signal,

the maximum RF voltage sustainable by the diodes would be 850 volts peak. Highest RF voltage would be incident for the 180° phase shifter case; and, for a 50 ohm system employing a 3 db hybrid coupler, the peak power would be limited to approximately 3.5 kilowatts. For a CW power rating of 750 watts the RF duty cycle would be 0.2, and this may be excessive for most system applications. Voltage reduction by RF transformers and iterative transmission line loading techniques--as discussed in the previous report--therefore will be sought to exploit more fully the RF phase control capability of these high heat dissipation diode packages.

2. Overcoming the Peak Power Voltage Limitations by Small Increment Phase Steps.

Considerable investigation has been performed to describe the phase shifter circuit consisting of a 3 db hybrid coupler with symmetric reflective terminations containing semiconductor diodes attached to the "3 db" arms. This circuit is diagrammed in Figure 1.

Using presently available switching diodes and a circuit characteristic impedance of 50 ohms, the peak power capability of the phase shifter is usually limited by the maximum RF voltage which may be sustained by the diode under reverse bias. This voltage, for a given power level, is in turn a function of the length of the shorted line, depicted as $\theta/2$, behind the shunt mounted diode, since the impedance of the reverse biased diode circuit branch approaches a near open-circuit value. The step phase shift to be obtained is nearly θ if the reactance of C_s is selected to series resonate L_s when the diode is forward biased. Then the RF voltage, V_{oc} , appearing across the diode shunt circuit branch may be expressed in terms of the phase shift, θ , as follows, Refer to Figure 2.

The reflection coefficient under forward bias, Γ_o , is approximately -1 if R is much smaller than Z_o and series tuning using C_s is effected to eliminate the net diode circuit branch reactance.

Then

$$\Gamma = \frac{jX - Z_o}{jX + Z_o} \quad \text{Equation 1}$$

$$|\Gamma - \Gamma_o| = \left| \frac{jX/Z_o}{1 + jX/Z_o} \right| = \left| \frac{V_{oc}}{V_L} \right| \quad \text{Equation 2}$$

and using complex algebra it can be shown that,

$$|\Gamma - \Gamma_o| = |2 \sin \theta/2| \quad \text{Equation 3}$$

where θ is the phase shift obtained. The peak power incident on the single termination then is given by,

$$\text{Peak Power} = \frac{V_L^2}{Z_o} = \frac{V_{oc}^2}{Z_o} \cdot \frac{1}{4 \sin^2 \theta/2} \quad \text{Equation 4}$$

Since two terminations are used--and each sees half of the total peak power, P_m , incident on the phase shifter is given by:

$$P_m = \frac{V_{oc}^2}{Z_o} \cdot \frac{1}{2 \sin^2 \theta/2} \quad \text{Equation 5}$$

Equation 5 predicts that the peak power, P_m , that may be withstood by the phase shifter is increased if the phase shift θ , is decreased. To verify this equation two diodes of known breakdown voltage were mounted in a strip line circuit--as characterized by Figure 1--and increasing RF power applied until reverse bias leakage current of 6 microamperes per diode was drawn indicating that a limiting value of RF power had been reached. It was found that RF levels causing more than 10 microamperes of leakage rapidly resulted in permanent deterioration of the reverse breakdown characteristic of the diode and attendant diode failure.

A reverse bias of -100 volts was applied to each diode. Their breakdown voltages were approximately 1000 volts, for this voltage the low frequency VI characteristic is diagrammed in Figure 3 where the assumed effect of an applied RF voltage is shown superimposed.

Phase shift was adjusted to 180° and diode reverse bias leakage conduction occurred at an RF power level of 2.5 kilowatts. Operation was at 1300 mc with a pulse length of 1 microsecond and a duty cycle of 0.001. This suggested that the maximum RF voltage sustainable was 700 volts peak. Since the applied reverse bias was 100 volts, the reverse leakage of 6 microamperes with applied RF suggests that the diode has an effective RF breakdown of 800 volts peak.

In similar fashion, the phase shift was varied and the power level noted at which 6 microamperes reverse bias leakage was obtained. A value of 500 volts (RMS) was chosen for V_{oc} and 50 ohms for Z_o . The resultant calculated and measured variation of peak power with phase shift is shown in Figure 4. Since the monitoring of leakage current is not a sensitive means of determining when a particular value of RF voltage appears across the diode, RF power, a quadratic function of voltage is even less sensitive to this measurement. Nevertheless, calculated and measured results are seen to agree within about 35%.

Power was increased to 48 kilowatts by decreasing the phase shift to 21° and neither diode failed. Arcing in the stripline coupler at 50 kilowatts prevented higher power operation. The insertion loss of the phase shifter was essentially independent of phase shift for all values of short position except that which yielded 0° phase shift, at which the short reflects a zero impedance across the diode and diode losses are eliminated. As may be seen from Figure 5,

the insertion loss at forward bias was about 0.6 db. Since the corresponding diode resistance at forward bias was 0.5 ohms, the diode dissipative loss obtained when the diode shorts a 50 ohm line should be only 0.18 db. Coupler loss was therefore, estimated at 0.4 db which must be dissipative because the input VSWR was 1.2 or less, accounting for a reflective loss of only 0.05 db.

Such losses seemed unusually high; similar phase shifters had been constructed previously with less than 0.3 db total losses, and this effect therefore should be reducible.

3. Obtaining Maximum Phase Shift Per Diode in an Iterative Loaded Line Phase Shifter

In the Fourth Quarterly Report results obtained with an iterative loaded transmission line phase shifter prototype were cited. This approach is well suited to phase shifting, distributing the diodes for high power operation. A general equivalent circuit for a two susceptance state line loading element $j\bar{B}_{1,2}$ is shown in Figure 6. As was mentioned previously, matched transmission may be approximated well by keeping the value of $\sqrt{\bar{B}_{1,2}}$ small and spacing shunt element pairs by θ , a quarter wavelength. The phase shift to be obtained per section is then given by

$$\text{Phase Shift} = \Delta\phi = \phi_1 - \phi_2 \quad \text{Equation 6}$$

$$\Delta\phi = \cos^{-1} (\cos \theta - \bar{B}_1 \sin \theta) - \cos^{-1} (\cos \theta - \bar{B}_2 \sin \theta)$$

$$\text{Equation 7}$$

$$\text{If } \sqrt{\bar{B}_{1,2}} < 0.5$$

and since θ is chosen equal to 90°

$$\left| \frac{\Delta\varphi}{\sim} \right| \left| \bar{B}_1 - \bar{B}_2 \right| \text{ radians} \quad \text{Equation 8}$$

$$\left| \frac{\Delta\varphi}{\sim 57} \right| \left| \bar{B}_1 - \bar{B}_2 \right| \text{ (degrees)} \quad \text{Equation 9}$$

It may be seen from equation 9 that for a given magnitude of normalized shunt susceptance, $\bar{B}_{1,2}$ the maximum phase shift will be obtained when \bar{B}_1 and \bar{B}_2 are of opposite sign, and this could be obtained if a change in the diode bias causes the net shunt susceptance to change from a capacitive to an inductive value.

Such a feature may be realized practically in the coaxial circuit diagrammed in Figure 7, wherein diode pairs are spaced along the line by a quarter wavelength, shown as θ , so that their reflected waves cancel to yield matched transmission. An equivalent circuit is shown in Figure 8.

This circuit utilizes the diodes junction capacity and the parasitic series inductance, inherent reactive circuit elements, to advantage as the necessary switched reactances. The shunt susceptance, \bar{B}_1 will be defined for the forward bias diode state. The equivalent circuit then will be inductive and

$$j\bar{B}_1 = \frac{1}{j\bar{X}_L} \quad \text{Equation 10}$$

where the bar denotes normalized quantities. Similarly under reverse bias,

$$j\bar{B}_2 = \frac{1}{j\bar{X}_L - j\bar{X}_C} \quad \text{Equation 11}$$

The phase shift is found by combining Equations 9, 10, 11 to be

$$\left| \frac{\Delta\varphi}{\sim 57} \right| \left| \frac{\bar{X}_C}{\bar{X}_L^2 - \bar{X}_L \bar{X}_C} \right| \text{ (degrees)} \quad \text{Equation 12}$$

If the diode capacitance is chosen so that

$$\left| \bar{X}_C \right| = 2 \left| \bar{X}_L \right| = X \quad \text{Equation 13}$$

Then

$$j\bar{B}_1 = -j\bar{B}_2$$

yielding maximum phase shift with a minimum value of $\left| j\bar{B}_{1,2} \right|$, and minimal reflection in either of the diodes' bias states. Under these conditions that phase shift would be given by

$$\left| \Delta\phi \right| \approx \frac{228}{X} \text{ degrees} \quad \text{Equation 14}$$

For example, if a phase shift of $22\frac{1}{2}$ degrees per section is desired then

$$X \approx 10 \quad \text{Equation 15}$$

For a switching diode with reverse bias capacity of, typically, 0.8 PF, and a desired phase shifter operating frequency of 3000 Mc,

$$\begin{aligned} X_C &= -j 66 \text{ ohms} \\ X_L &= +j 33 \text{ ohms} \\ L &= 1.8 \text{ nanohenries} \\ Z_0 &= 6.6 \text{ ohms} \end{aligned} \quad \text{Equation 16}$$

These values appear very practically realizable, and the low value of Z_0 increases the usual reverse breakdown power limit of the diodes; about 8 times the line power tolerable in a 50 ohm system thusly may be withstood by the shunt mounted diodes. A value of 250 volts (RMS) line voltage could permit RF transmission of over 10 kilowatts in the 6.6 line.

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The diode iterative loaded transmission line appears a feasible technique for obtaining high power phase shifting and experiments will be performed in the coming quarter to evaluate it directly.

CONCLUSIONS

A device yielding 90° of phase shift at 1300 mc at a power level of 750 watts peak with 500 microsecond pulse length was constructed using 4 water cooled PIN diodes to terminate a 3 db hybrid coupler. Peak power was theoretically limited to 3.5 kilowatts by the diode reverse bias voltage considerations, and impedance transforming techniques could be used to increase this value. Insertion loss in either diode state was about 0.3 db.

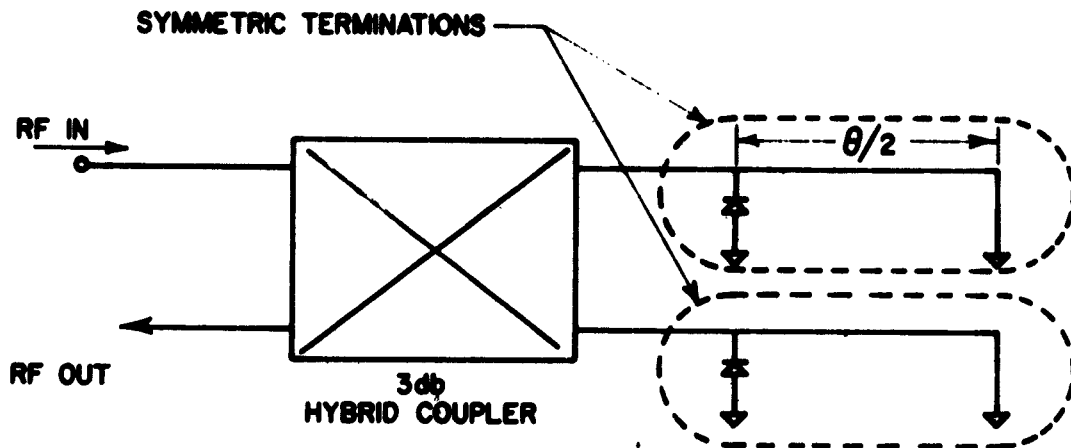
A stripline phase shifter was tested to 48 kilowatts at 1300 mc. Insertion loss was 0.6 db and phase shift was 21.5 degrees. It was shown that a compromise exists between the maximum voltage limited power level and the obtained phase shift, and this is expressed by,

$$P_m = \frac{V_{oc}^2}{Z_o} \cdot \frac{1}{2 \sin^2 \theta/2}$$

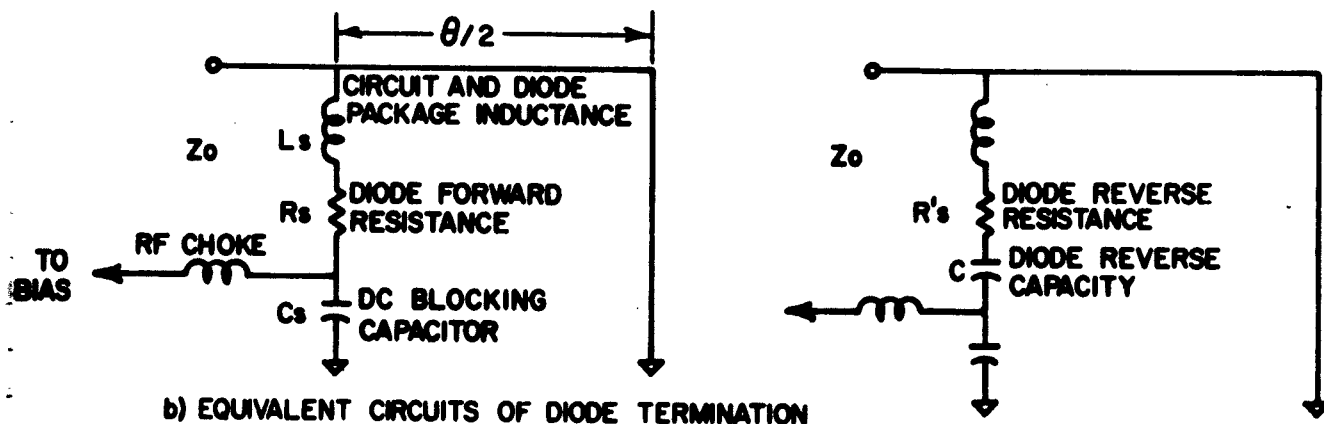
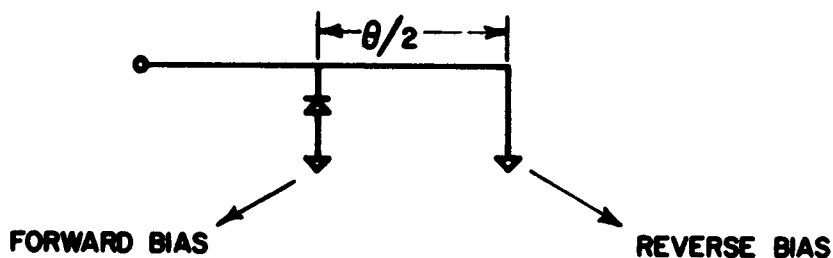
A proposed S band step phase shifter constructed by diode iterative loaded coaxial line was described which could yield 22.5 degrees of phase shift using typical PIN switching diodes at power levels exceeding 10 kilowatts. Further efforts to evaluate experimentally this phase shifting technique will be made in the next quarter.

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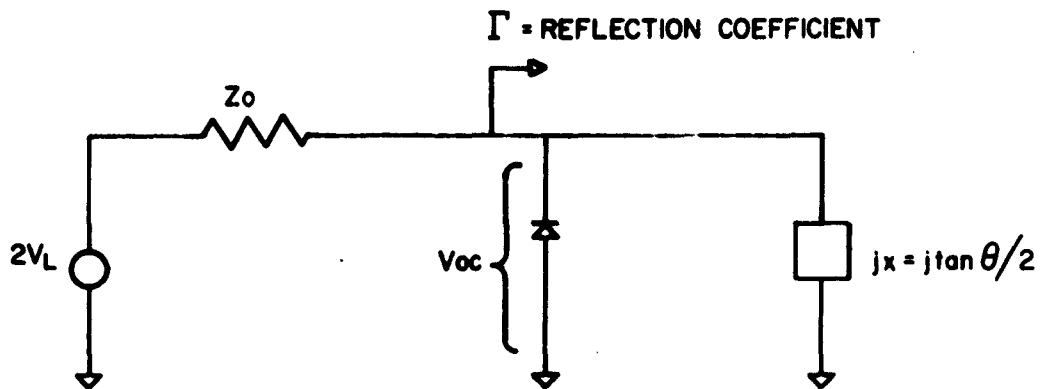
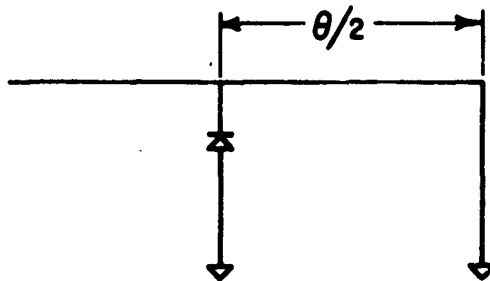


a) TRANSMISSION-REFLECTION PHASE SHIFTER



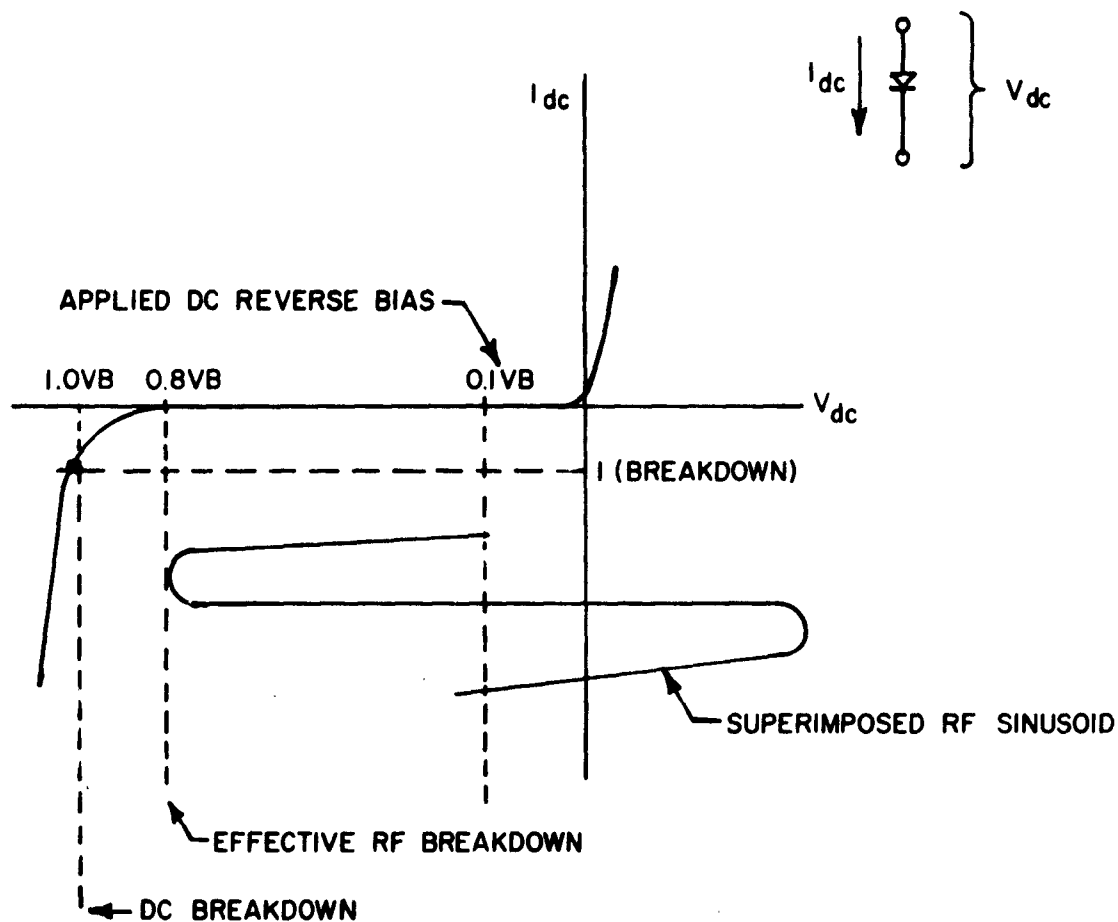
b) EQUIVALENT CIRCUITS OF DIODE TERMINATION

FIGURE 1



EQUIVALENT CIRCUIT OF SINGLE PHASE SHIFTER TERMINATION
SHOWING THEVENIN EQUIVALENT RF POWER SOURCE

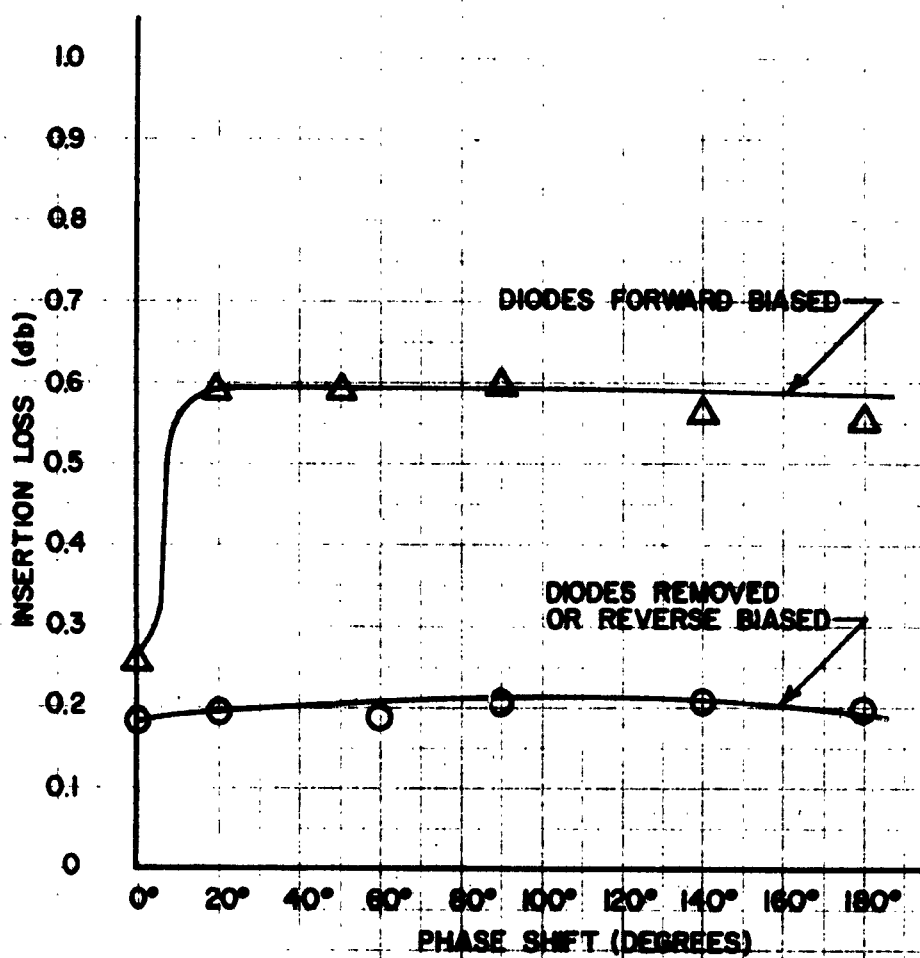
FIGURE 2



LOW LEVEL PIN DIODE V vs. I CHARACTERISTIC SHOWING
SUPERIMPOSED RF VOLTAGE AND OBSERVED EFFECTIVE RF BREAKDOWN.

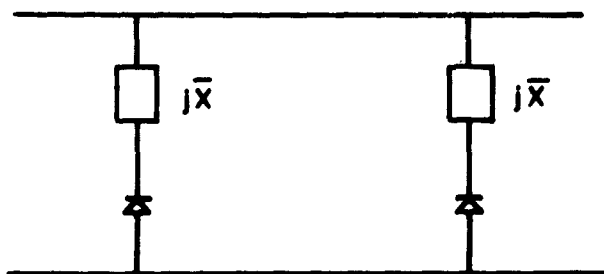
FIGURE 3



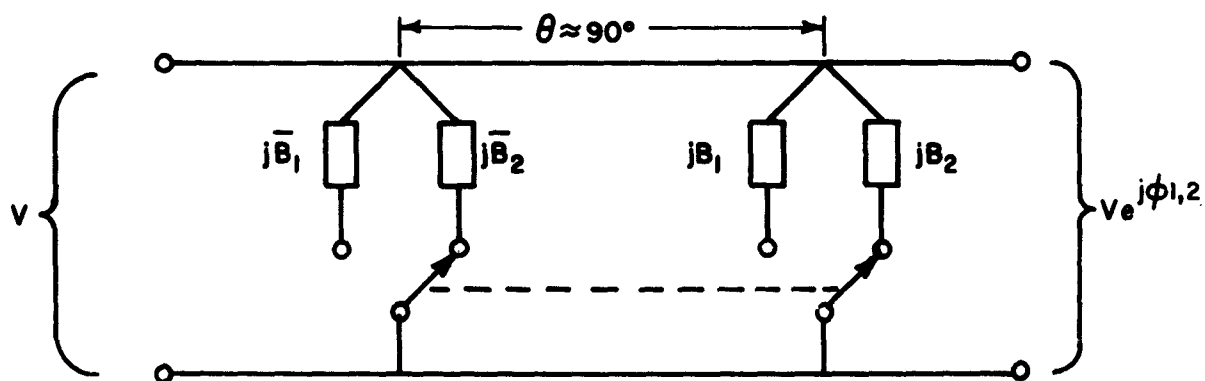


INSERTION LOSS VS PHASE SHIFT CHARACTERISTIC
OF STRIP LINE TRANSMISSION-REFLECTION PHASE SHIFTER.

FIGURE 5

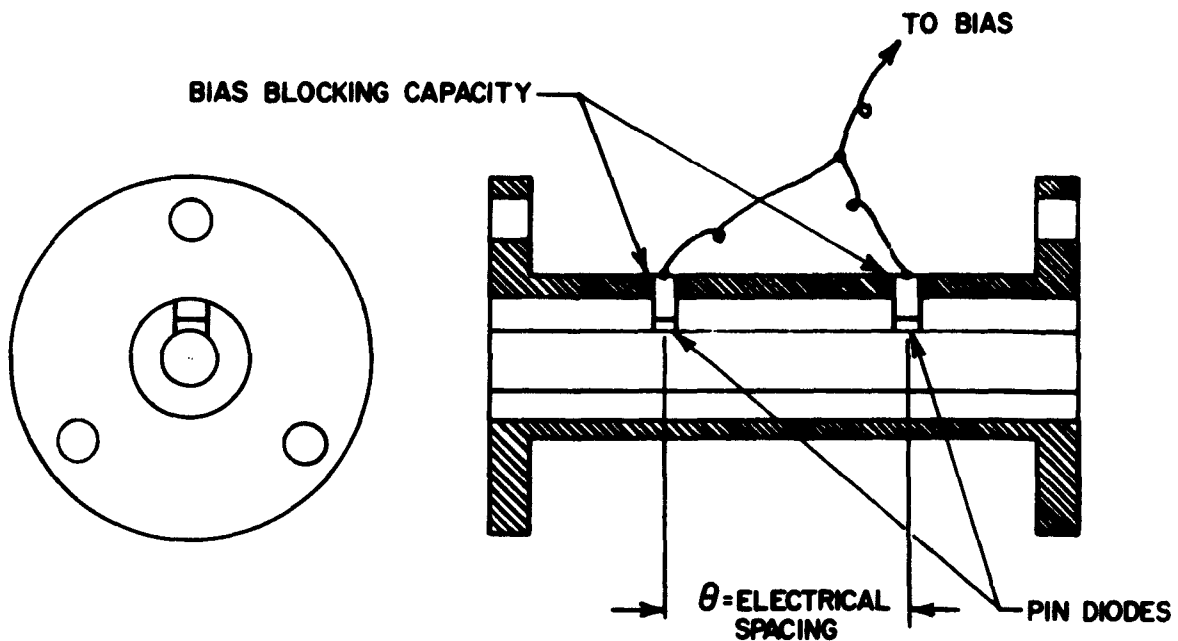


PROTOTYPE SECTION SCHEMATIC

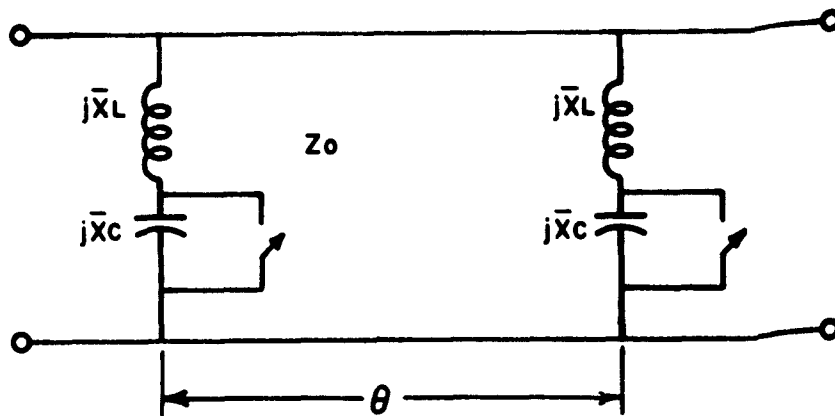


EQUIVALENT CIRCUIT

TRANSMISSION TYPE STEP PHASE SHIFTER PROTOTYPE SECTION
FIGURE 6



DIODE ITERATIVE LOADED LINE PROTOTYPE
FIGURE 7



EQUIVALENT CIRCUIT OF DIODE ITERATIVE LOADED LINE PROTOTYPE
FIGURE 8